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ANTIPROTON-PROTON ANNILHILATION INTO
FOUR AND FIVE PIONS, AT 2.7 BEV/C.

Iowa State University of Science and Technology
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ANTIPROTON-PROTON ANNIHILATION
INTO FOUR AND FIVE PIONS,
AT 2.7 BEV/C

by

Donald Edward Lyon, Jr.

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Physics

Approved:

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Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa

1966

TABLE OF CONTENTS

	Page
I. INTRODUCTION	1
II. EXPERIMENTAL PROCEDURE	2
A. The Beam	2
B. Data Collection	3
C. Data Handling	3
III. THE FIVE PION FINAL STATE	6
A. Effective Mass Spectra	6
B. Examination of Biases	14
C. The G Meson	17
1. History	17
2. Quantum numbers	18
3. Decay modes	19
IV. THE FOUR PION FINAL STATE	24
V. CROSS SECTIONS	27
VI. BIBLIOGRAPHY	28
VII. ACKNOWLEDGMENTS	29

1. INTRODUCTION

This paper is the result of an experiment carried out at Brookhaven National Laboratory during September, 1964 that used the Shutt 20" liquid hydrogen bubble chamber in separated beam number one, which was set up for 2.7 BeV/c antiprotons. The specific topics covered here are the multi-pion final states resulting from antiproton-proton annihilations. Three other experiments concerning this problem have been performed recently. One of these was at Berkeley with 1.6 BeV/c antiprotons (1), one at Yale with 3.3 BeV/c and 3.7 BeV/c antiprotons (2), and one at Bonn University with 5.7 BeV/c antiprotons (3). The endeavor of this work is to add to the information accumulated by examining antiproton-proton annihilations at an energy intermediate to the other cited works.

II. EXPERIMENTAL PROCEDURE

All bubble chamber experiments to date have employed a particle accelerator to produce the particles to be studied, a beam transport system to get them into the chamber, and scanners to find the interactions in photographs taken of the chamber. In this section, therefore, only those features of the beam, data collection, and analysis will be presented that are necessary for the discussion of the four and five pion final states.

A. The Beam

The beam was an electrostatically separated beam of antiprotons from the Brookhaven National Laboratory alternating gradient proton synchrotron with a momentum of 2.7 BeV/c and a momentum spread of $\pm 1\%$. The average flux of antiprotons in the chamber was 13 per picture.

To get an estimate of beam purity a search was made of the zero-prong-two-vee events for kinematic consistency with the reaction

$$\pi^- + P \rightarrow \Lambda^0 + K^0 ,$$

with negative results. Also, since the maximum laboratory opening angle in antiproton-proton elastic scattering is 90° a search was made for kinematic consistency of the two-prong events whose opening angle was greater than 90° , with the reaction

$$\pi^- + P \rightarrow \pi^- + P .$$

Here again, none were found. This evidence, when combined with experimental information taken at run time, produced the estimate that the beam was

99% \pm 1.0% antiprotons with any contamination presumably due to μ mesons, which do not strongly interact.

B. Data Collection

Approximately 100,000 photographs were obtained in this exposure and we have used \sim 20,000 of these so far in the analysis of the four-pronged events for the reactions

$$\bar{P} + P \rightarrow \pi^+ + \pi^+ + \pi^- + \pi^- \quad (1)$$

$$\rightarrow \pi^+ + \pi^+ + \pi^- + \pi^- + \pi^0 \quad (2)$$

Scanning for events was accomplished using Prevost projectors and a viewing table assembly constructed here at Iowa State. The topology of the events for both channels is one incoming beam track and four visible outgoing tracks. With this simple topology the scanning efficiency, determined by scanning the same film a second time, was 94.7%. The measuring of events was performed using two Itek automatic track centering and following digitized stages. A total of 3,000 events from a restricted fiducial volume of the chamber was measured. However, the sample contains only those events found in the first scan of the film and the re-measures of these which, because of measuring errors, failed the first time through the spatial reconstruction program.

C. Data Handling

The program DATPRO, written originally at Brookhaven and modified here at Iowa State University, was used for the spatial reconstruction of events. Information from each "reconstructed" event was then stored on magnetic

tape for input to the GUTS routine. A version of the GUTS routine, modified here at Iowa State, was used for the kinematical analysis of the data and the output from this program was again stored on magnetic tape for later analysis. Every possible constrained final state of the $\bar{P}P$ system going to four visible prongs was considered; the attempt for a fit being made only when the missing mass for a particular hypothesis was within 3.0 standard deviations of the corresponding neutral particle. A chi-square cut-off of

$$\chi^2 = 2.0 \left(\frac{\text{number of}}{\text{constraints}} \right) + 7.0$$

was set so that only fits with χ^2 less than this are in the final sample. With these criteria, a total of 84 events fell into the four pion channel and 654 fell into the five pion channel.

The four pion channel is a fairly clean sample since it is a four constraint problem and 47 of the 84 events in this final state fit uniquely. The rest of the events had only one other kinematic ambiguity, namely, with the five pion channel. However, the χ^2 distribution for the five pion fit was not characteristic of a one constraint distribution and the CM momentum of the π^0 was in every case less than 150 MeV/c. For these reasons the total sample of 84 events was used in the analysis of the four pion final state.

The sample of events used for the analysis of the five pion final state had kinematic fits distributed this way:

<u>EVENTS</u>	<u>FIT</u>	<u>CLASS</u>
455	$2\pi^+ 2\pi^- \pi^0$ and no other constrained fit	(a)

107

$$K^+ 2\pi^- \pi^+ \bar{K}^0 \quad \overset{2\pi^+ 2\pi^- \pi^0}{\text{and/or}} \quad K^- 2\pi^+ \pi^- K^0 \quad (b)$$

92

$$K^+ 2\pi^- \pi^+ \bar{K}^0 \quad \overset{2\pi^+ 2\pi^- \pi^0}{\text{and/or}} \quad K^- 2\pi^+ \pi^- K^0 \quad (c)$$

$$K^+ K^- \pi^+ \pi^- \pi^0$$

Here again the χ^2 distribution of the $2K3\pi$ fits for events in class (b) was not characteristic of a one constraint problem while the 5π χ^2 distribution was characteristic of a one constraint problem. Also, in almost every case the ratio $\chi^2_{5\pi}/\chi^2_{2K3\pi}$ was less than one. The events in class (c) showed χ^2 distributions more like a one constraint problem for all the fits. Also, the CM momentum distribution of the corresponding neutral was reasonable. However, a detailed examination coupled with ion checking, to be presented herein, showed that the main contribution to biases in the mass spectra shown comes not from accidental fits involving strange particles, but from an accidental fit of the final state $2\pi^+ 2\pi^- 2\pi^0$ to the five pion final state.

III. THE FIVE PION FINAL STATE

A. Effective Mass Spectra

To analyze the data for resonances, a comparison with the predictions of Lorentz invariant phase space was made of the distributions in the invariant masses

$$M_{1\dots n} = \left[\left(\sum_{i=1}^n E_i \right)^2 - \sum_{i=1}^n \vec{p}_i \cdot \sum_{j=1}^n \vec{p}_j \right]^{1/2}.$$

Here $n = 2, 3$, or 4 , E_i is the total energy of the i^{th} particle in the laboratory frame, and \vec{p}_i is its momentum in the same frame of reference. Only events from class (a) are included in the mass spectra shown since this class of events was found to be the least contaminated with events from the $2\pi^+2\pi^-2\pi^0$ channel; this contamination being $3\% \pm 3\%$.

The singly charged and neutral distributions for $n = 2$ are shown in Figure 1. These show the presence of the ρ meson in all three charge states but no other significant deviations from phase space. Rates for the ρ meson of $\sim 4\%$ in each charged state and $\sim 8\%$ in the neutral state were determined by subtracting the expected numbers of events in the mass range 700-800 MeV from the actual numbers of events in that mass range. The expected numbers were obtained by a least squares fit of the phase space curves to the data with the mass range 700-800 MeV deleted, and extrapolation of the resulting curves into this mass range. The doubly charged two body effective mass spectra were phase space distributed.

The singly and doubly charged distributions for $n = 3$ were also phase space distributed, but evidence for the presence of the ω meson exists in the neutral combination $\pi^+\pi^-\pi^0$ (Figure 2). Dalitz plots of this distribution

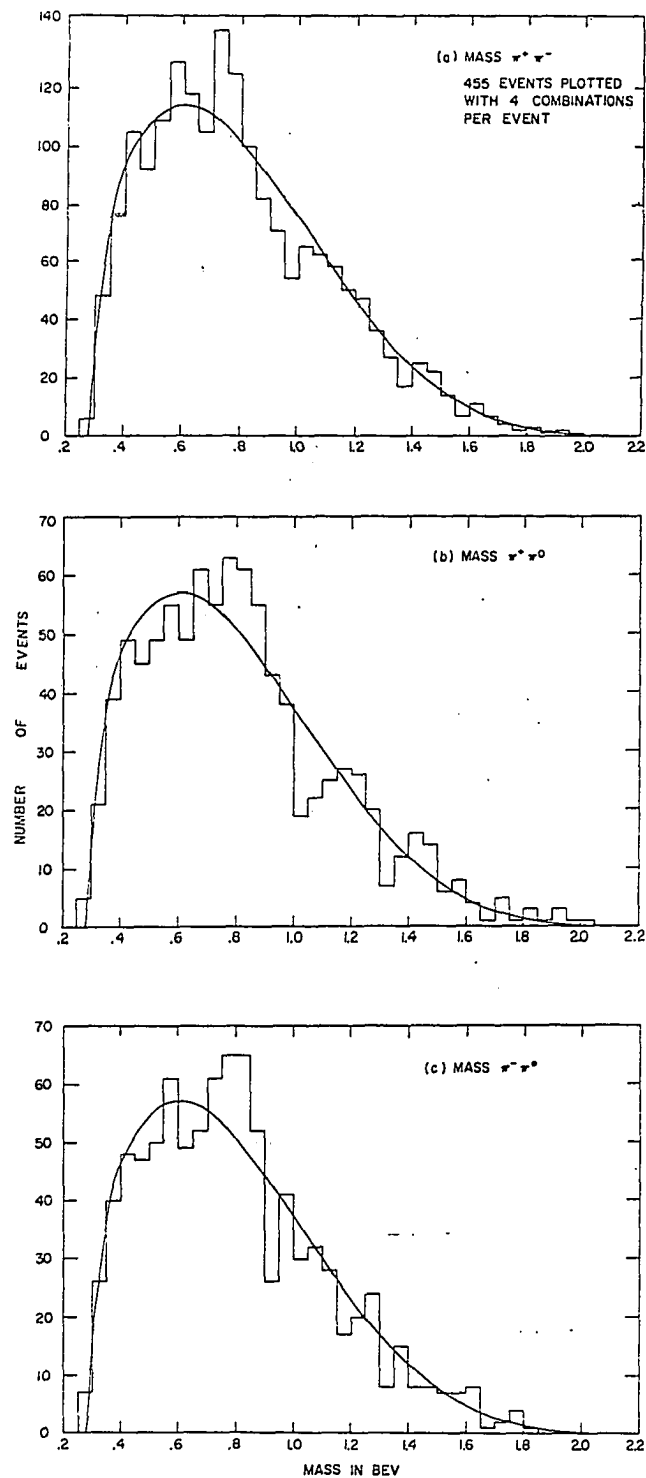


Figure 1. The smooth curves are the phase space distributions normalized to the area of each histogram.

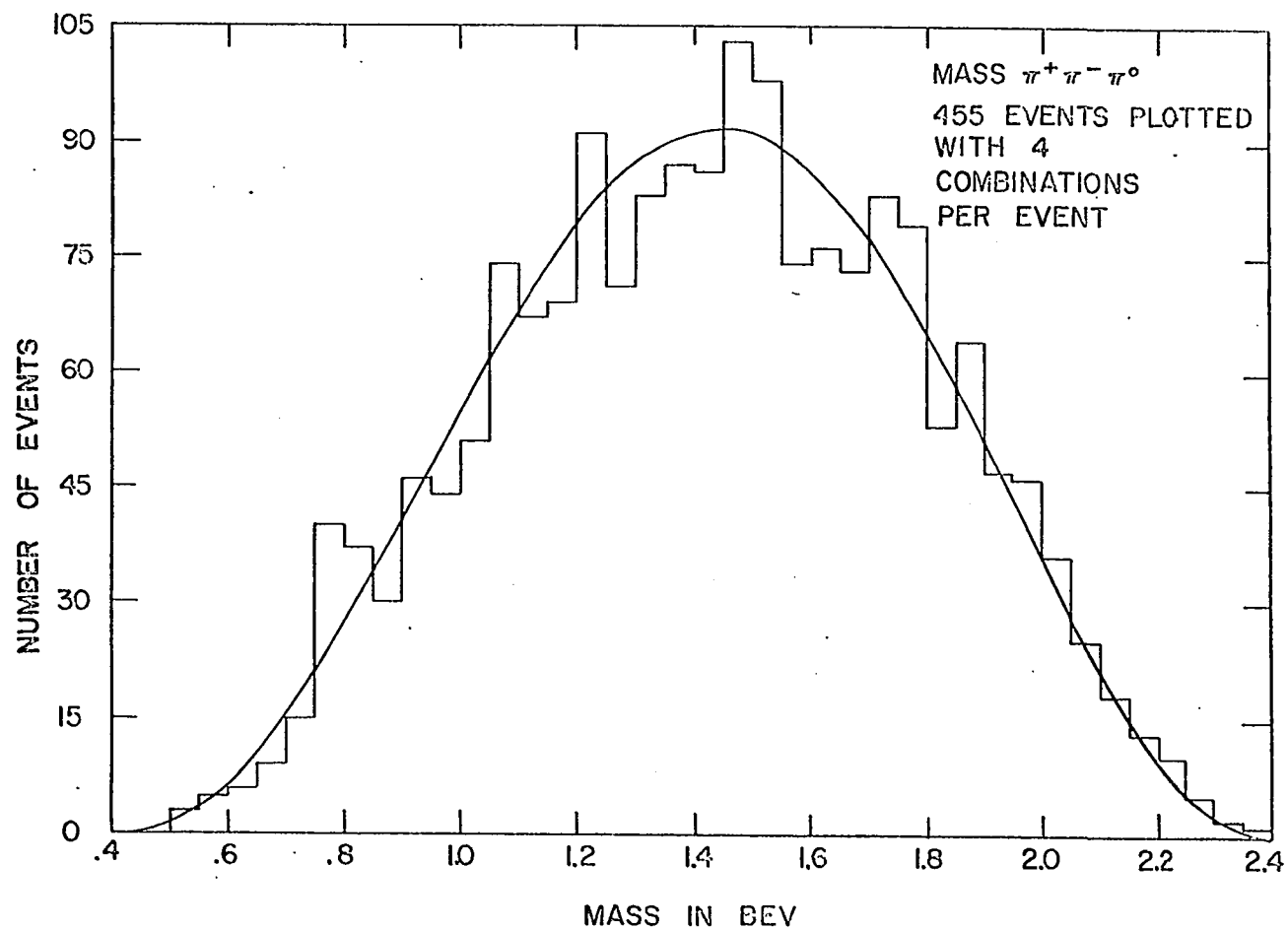


Figure 2. The smooth curve is the phase space distribution normalized to the area of the histogram.

versus the two body distributions revealed no apparent $\rho - \omega$ coincidences. The rate for the ω meson, determined again by subtraction, was $\sim 7\%$.

The distributions in the charged combinations for $n = 4$ are shown in Figure 3 and it is seen that here there are no significant deviations from the phase space curves. However, the neutral four body combination, shown in Figure 4, has a significant enhancement in the mass range 1550-1800 MeV and a fit of phase space plus a Breit-Wigner distribution to the data gives a value of 1630 ± 30 MeV for the mass of the resonance with ~ 25 events above background. The data is not very sensitive to variations in the width but the fitted value of Γ is 140 ± 50 MeV.

A plot of the production angular distribution of the neutral four body effective mass, in the zero momentum frame of the $\bar{p}p$ system and for events where this mass lies in the range 1550-1800 MeV, shows a peaking in the forward and backward directions, where "forward" is defined as the anti-proton direction. This distribution is the same as the angular distribution of the π^0 in that frame and is shown in Figure 5. The plot is in contrast with the apparently isotropic angular distributions of the π^0 for control ranges 200 MeV wide on either side of 1550-1800 MeV and constitutes independent evidence for the existence of a resonance in this mass range. The anisotropy of the distribution suggests the plots of the neutral four body effective mass spectrum for special ranges of $|\cos \theta_{\pi^0}^{cm}|$ shown in Figure 6. Comparison of the enhancements in the mass range 1550-1800 MeV of the two plots with roughly determined phase space curves indicates that the resonance is produced with $|\cos \theta_{\pi^0}^{cm}| \geq .8$ approximately 95% of the time.

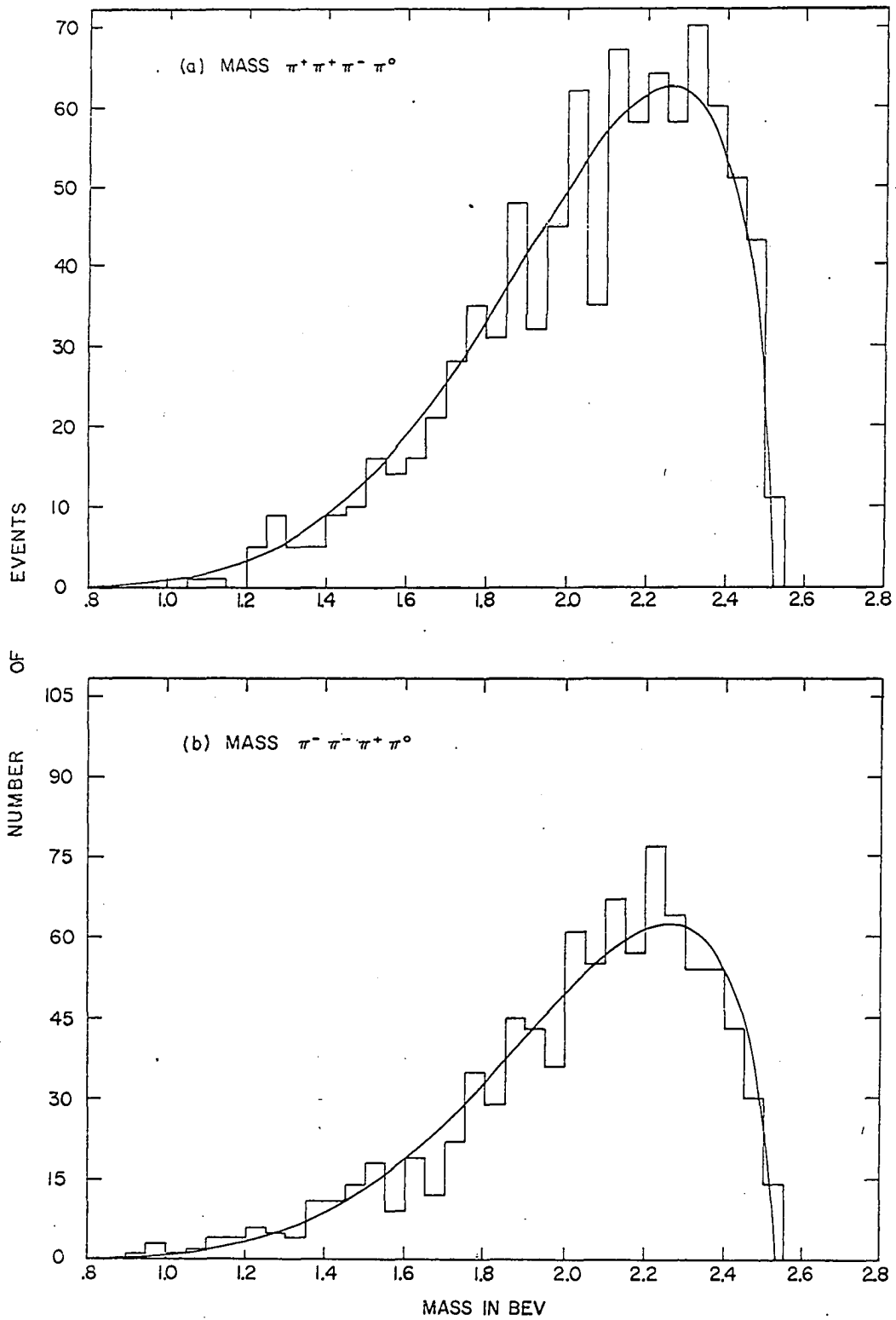


Figure 3. The smooth curves are the best fits of phase space to the data.

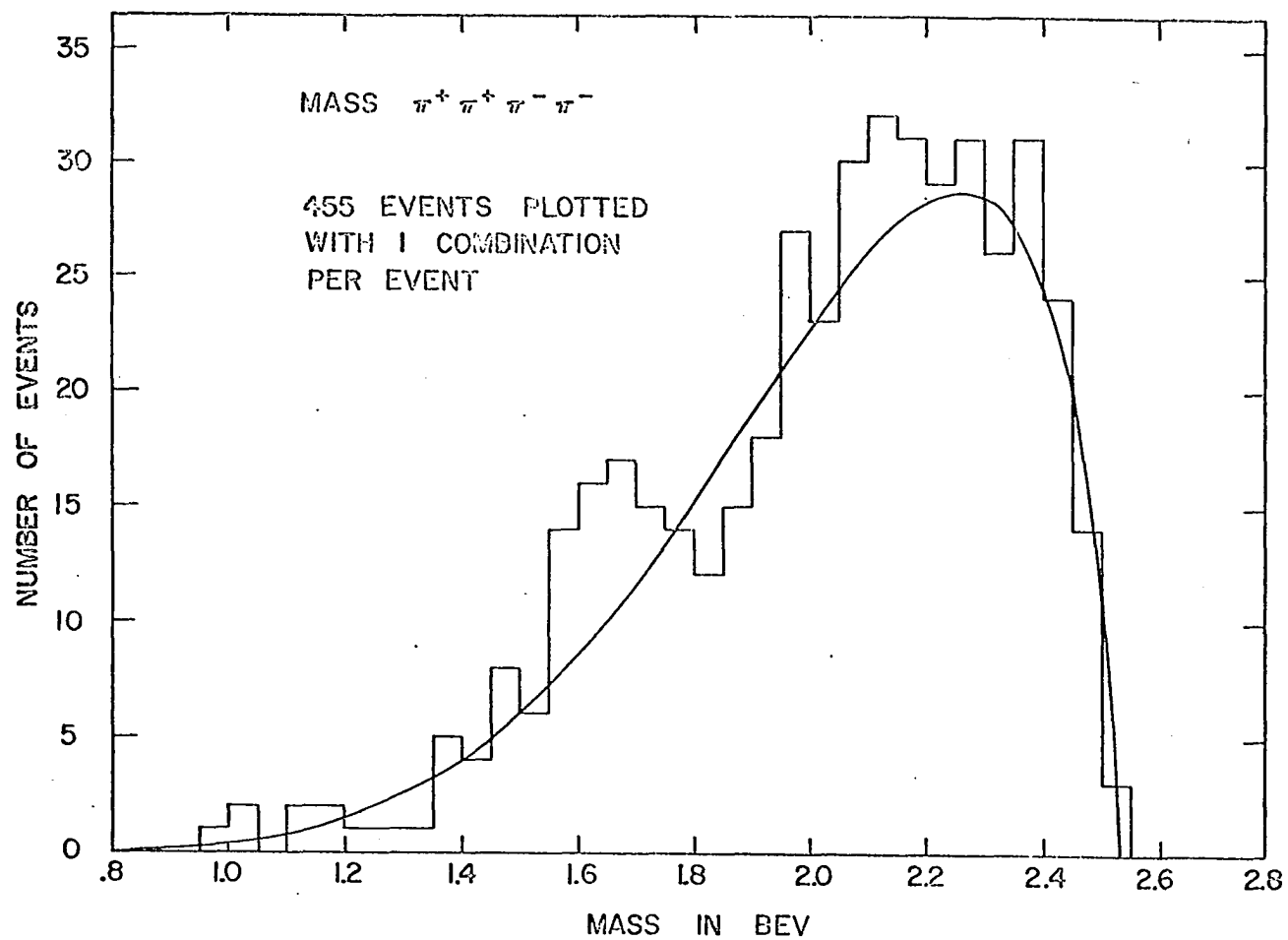


Figure 4. The smooth curve is the best fit of phase space to the data with the mass range 1550 - 1800 MeV deleted. Using 30 data bins 0.05 BeV wide, a χ^2 of 18 was obtained for the fit.

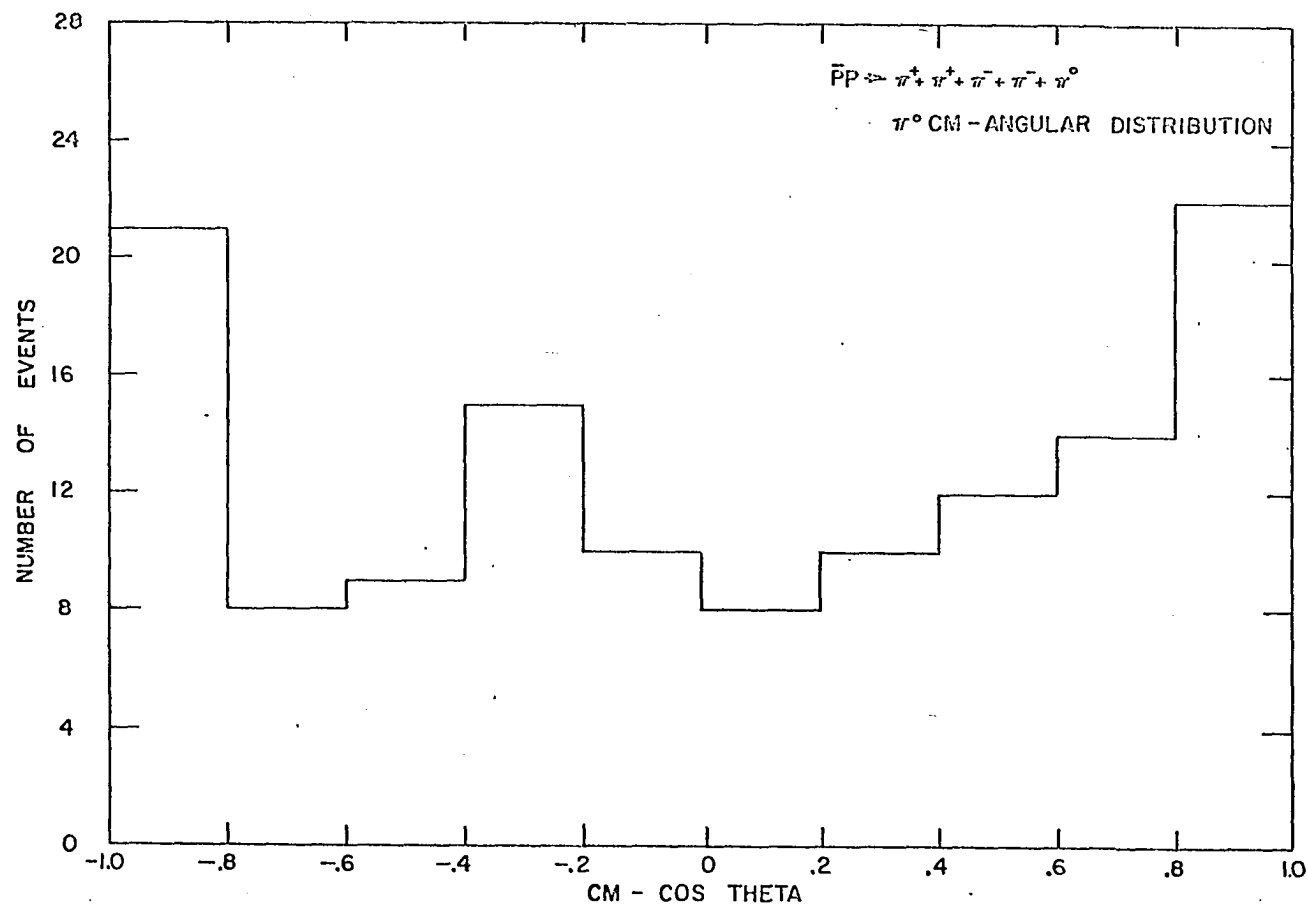


Figure 5. Events plotted are those for which $1800 \text{ MeV} \geq M_{\pi^+ \pi^+ \pi^- \pi^-} \geq 1550 \text{ MeV}$.

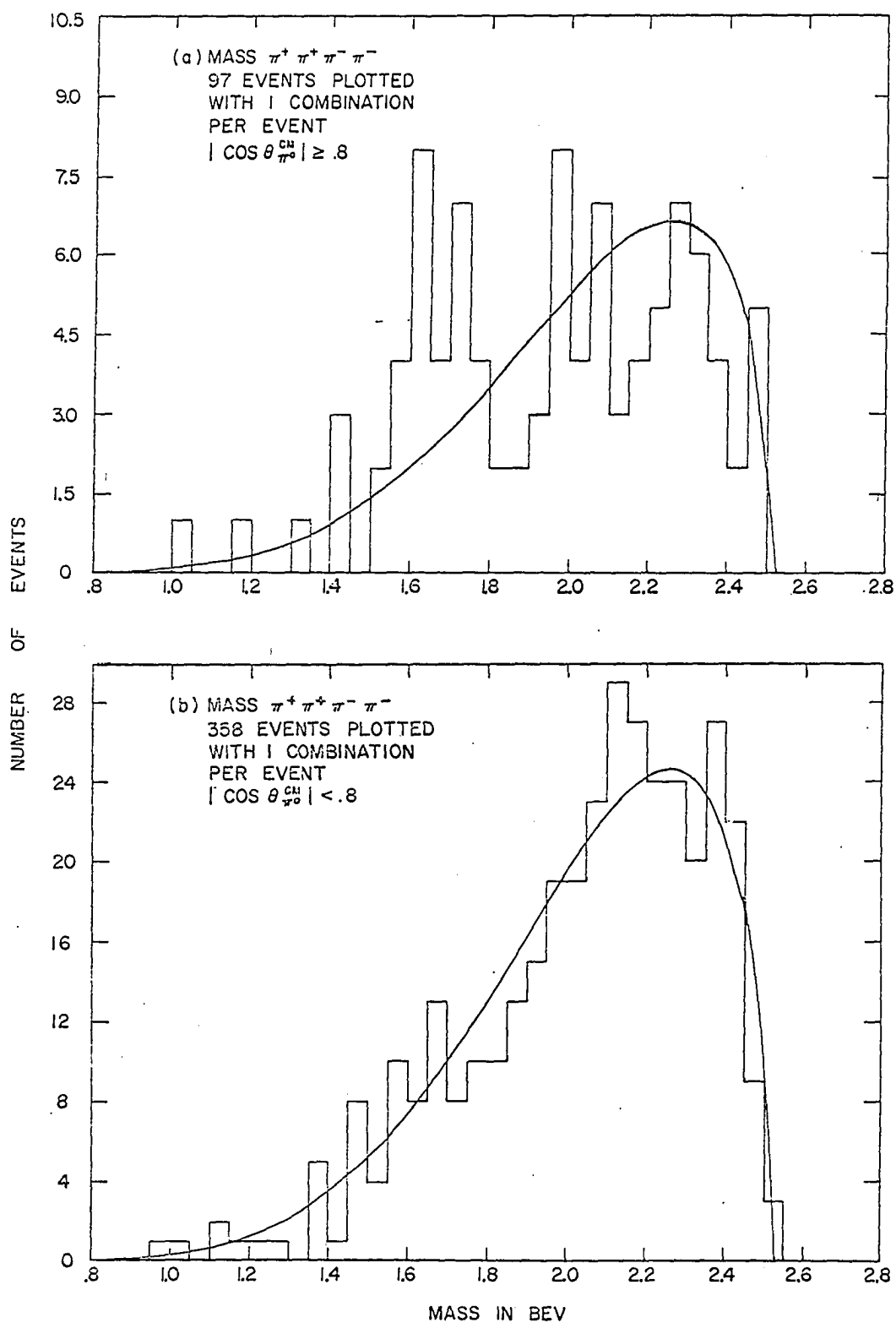


Figure 6. The smooth curves are the phase space distributions normalized to the area of each histogram.

B. Examination of Biases

There are a number of final states that might be giving accidental fits to five pions thus biasing the neutral four body effective mass spectrum. They are Dalitz pair events, events involving strange K mesons, and events from the $2\pi^+2\pi^-2\pi^0$ channel. A contamination from events that are two or three pion production without annihilation is unlikely since kinematic inconsistency with these channels was required of events classified as five pion final states, and ionization checks at the scanning table produced no likely candidates for them from events in class (a).

Dalitz pair events would be expected to give a $\pi^+\pi^-$ effective mass spectrum distorted at the low energy end of phase space since the relative energy of the combination should then be that of an electron positron pair and not of a pair of pions. Figure 1a, however, has no such distortion.

The K meson contamination is considered to be negligible for two reasons: one is that at this energy the cross sections for channels with strange particles present in the final state are much smaller than those without strange particles. The other is that bubble counting a sample of ~ 100 five pion events produced the estimate that less than one event whose neutral four body effective mass falls in the range 1550-1800 MeV with $|\cos \theta_{\pi^0}^{\text{cm}}| \geq .8$ could be attributed to false identification of events involving K mesons.

The contamination from $2\pi^+2\pi^-2\pi^0$ events that accidentally fit to five pions was checked by performing a least squares fit of a linear superposition of the $\frac{3\pi}{5\pi}$ and $\frac{3\pi}{6\pi}$ phase space curves to the experimental distribution in the effective mass combinations $\pi^+\pi^+\pi^-$ (Figure 7). The three body

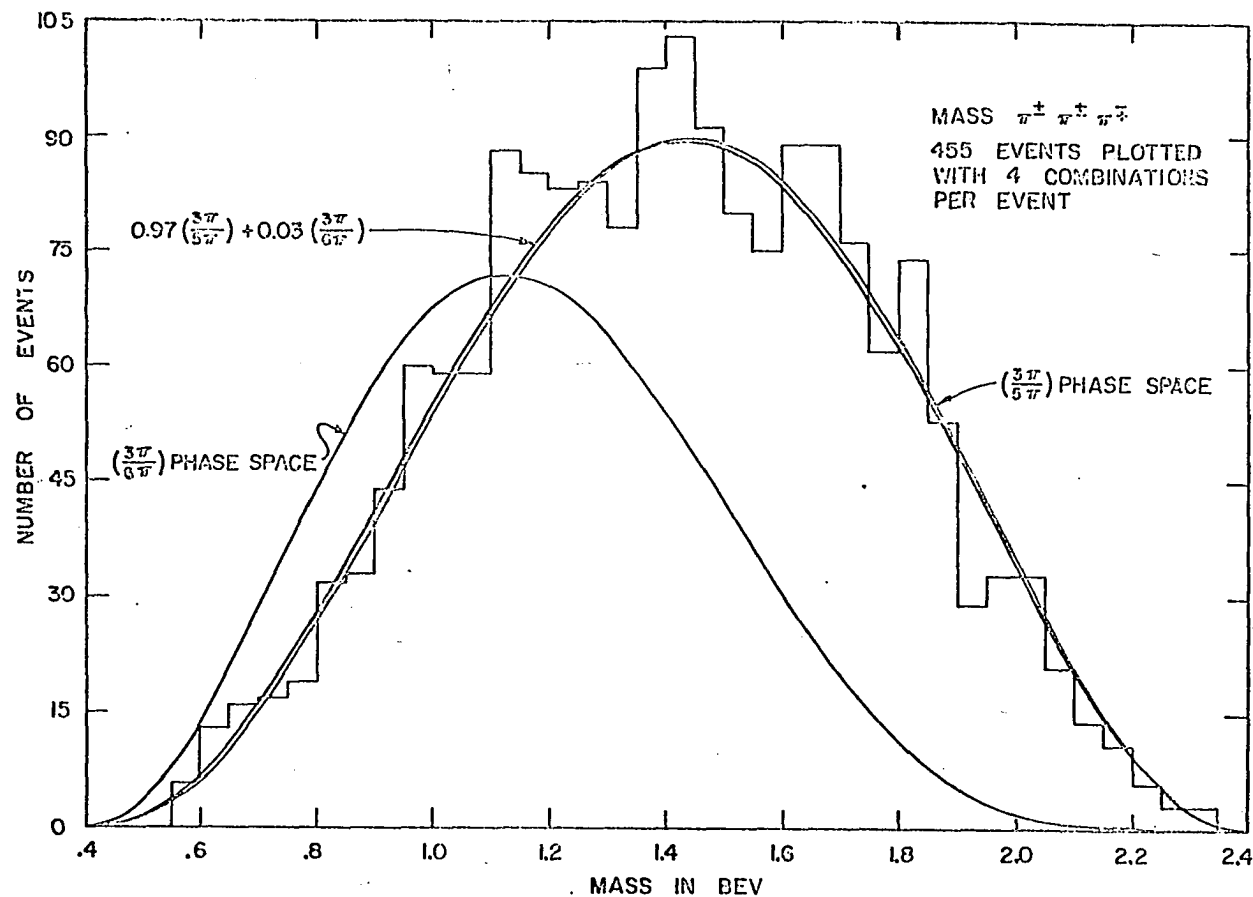


Figure 7. A least squares fit of $\frac{3\pi}{5\pi}$ and $\frac{3\pi}{6\pi}$ phase space to the data was performed to determine the 6π contamination. Using 40 data bins 0.05 BeV wide, the best fit was obtained with a linear superposition of $97\% \pm 3\%$ of the 5π and $3\% \pm 3\%$ of the 6π phase space curves. The χ^2 for the fit was 41.6.

combinations involving the π^0 were not used because the fitting process produces a π^0 that will conserve momentum and energy for the five pion hypothesis thereby faking a $\frac{3\pi}{5\pi}$ distribution, whereas the charged pions are measured quantities whose values will not change much in the fitting process and thus will have a three body distribution reflecting the state they come from. Using 40 data bins 0.05 BeV wide, the best fit was obtained with a superposition of $97\% \pm 3\%$ of the 5π and $3\% \pm 3\%$ of the 6π phase space distributions; the χ^2 for the fit being 41.6. This corresponds to a contamination of the events in class (a) with 14 ± 14 $2\pi^+ 2\pi^- 2\pi^0$ events.

The neutral four body effective mass distribution of such events was checked in two independent ways. Six pion events were randomly generated with a phase space distribution. Then two of the six particles were dropped and the remaining four were run through the kinematical analysis programs, using the experimentally determined distributions in track length and errors on measured quantities. Real six-prong events that fit uniquely to the hypothesis $3\pi^+ 3\pi^-$ were used to generate four-prong events and these were run through the kinematical analysis programs too.¹ In both cases no unusual build up in the 1550-1800 MeV range of the neutral four body effective mass plot was observed. In particular, there were no changes in the angular correlation of the $\pi^+ \pi^+ \pi^- \pi^-$ mass with the antiproton direction as the mass of the sample considered passed through the 1550-1800 MeV range. For events in class (a), a subtraction from the $\pi^+ \pi^+ \pi^- \pi^-$ mass spectrum of 3% of the 455 events there, distributed like the corresponding

¹The six-prong events are being analyzed by Daryl E. Bohning and are as yet unpublished.

spectrum of the generated events that fell in class (a), removed only 1 event from the 25 above background in the mass range 1550-1800 MeV.

A similar analysis of events in class (a + b) and (a + b + c) showed that their contaminations from the $2\pi^+2\pi^-2\pi^0$ channel were $13\% \pm 3\%$ and $18\% \pm 5\%$, respectively.

C. The G Meson

1. History

Two separate experiments carried out at CERN and published jointly (4) have each seen an effect, with approximately the same statistical validity, in the $\pi^+\pi^-$ effective mass distribution with the following results:

$$M = 1660 \pm 40 \text{ MeV}, \quad \Gamma = 170 \pm 40 \text{ MeV}^2$$

$$M = 1675 \pm 35 \text{ MeV}, \quad \Gamma = 200 \pm 50 \text{ MeV}^3$$

The authors of this work have proposed to call the resonance G. From this data one would assign a value of $1670 \pm 25 \text{ MeV}$ for the mass of the resonance and a width of $180 \pm 30 \text{ MeV}$. The mass value of the four pion system reported here differs from 1670 MeV by only 1.3 standard deviations. Thus, it seems at least possible that these are different decay modes of the same state. Another group working at CERN has observed an enhancement in the $\pi^+\pi^+\pi^-\pi^-$ mass spectrum at a mass value of $\sim 1650 \text{ MeV}^4$ (5).

²This experiment observes the reaction $\pi^+ + d \rightarrow p + \pi^+ + \pi^-$ for 6.0 BeV/C π^+ mesons.

³This experiment observes the reaction $\pi^- + p \rightarrow n + \pi^+ + \pi^-$ for 8.0 BeV/C π^- mesons.

⁴This experiment observed the reactions $\pi^+ + p \rightarrow p + 3\pi^+ + 2\pi^-$
 $\rightarrow p + 3\pi^+ + 2\pi^- + \pi^0$.

Two experiments performed separately, one with 8.0 BeV/C π^+ mesons and the other with 8.2 BeV/C π^- mesons, have investigated the reactions

$$\pi^+ + P \rightarrow P + \pi^+ + \pi^0 ,$$

and

$$\begin{aligned} \pi^- + P &\rightarrow P + \pi^- + \pi^0 \\ &\rightarrow n + \pi^- + \pi^+ . \end{aligned}$$

These experimenters reported seeing an enhancement in the $\pi^+\pi^0$ and $\pi^-\pi^0$ mass spectrum, respectively, at a mass value of ~ 1620 MeV (6,7). However, the second of these two saw nothing in the $\pi^+\pi^-$ mass spectrum where the effect is better established.

The authors of references 1 and 2 do not see the effect at all.

2. Quantum numbers

In the present experiment, the lack of an effect in the charged four pion combinations at the mass value 1630 MeV leads immediately to the assignment $l = 0$ for the isospin of the resonance. If one considers the effect observed in the neutral and charged two pion spectra to be the two body decay mode of the G, then its observation in the $\pi^\pm\pi^0$ spectra contradicts this assignment. One possibility is that what is observed in the $\pi^\pm\pi^0$ spectra is an $l = 1$ state whose mass is approximately the same as that of the $l = 0$ state reported here. If this is true then there exist two further possibilities: one is that the effects seen in the two and four pion spectra are entirely unrelated, thus preventing one from deducing other quantum numbers of either effect. The other is that the 1630 MeV resonance has both a two and a four pion decay mode, but that the present

limits on resolution and statistics in the two pion spectra prevent one from separating the two.

Another possibility is that there is only one resonance and either the $l = 1$ or $l = 0$ assignment is wrong. In any case the maximum amount of information is obtained if one assumes that the $l = 0$ assignment is correct and that there is a two pion decay mode of the G . In what follows this is the assumption that is made.

The G parity of a state of N pions is $G = (-1)^N$. Hence, the two and four pion decays both have $G = +1$. The observation of only these two decay modes is a reasonable basis for assuming G conservation in the decay, so $G = +1$ for the resonance. Then the relation $G = C (-1)^I$, which is valid for neutral meson states, gives $C = +1$. The two pion state is an eigenstate of CP with eigenvalue $+1$. This implies that C is $+1$, also. The parity of the two pion system is given by $P = (-1)^J$ so a positive parity for this state restricts J to even integer values. The A parity of the resonance is $+1$, since its two observed decay modes have $A = +1$.

3. Decay modes

A plot of the $\pi^+\pi^-$ mass spectrum for events from the experiment reported here whose $\pi^+\pi^+\pi^-\pi^-$ mass lies in the range 1550-1800 MeV shows a strong ρ signal and suggests an analysis of this spectrum for $\rho^0\text{-}\rho^0$ and $\rho^0\pi^+\pi^-$ decay modes of the G meson. To get an estimate of the ρ signal present in the spectrum from non-resonant events in the G mass range, use was made of the fact that G is produced with $|\cos \theta_{\pi^0}^{cm}| \geq .8$ approximately 95% of the time. The spectrum was re-plotted using only events with $|\cos \theta_{\pi^0}^{cm}| < .8$ (Figure 8a), and the ρ signal that remained was attributed

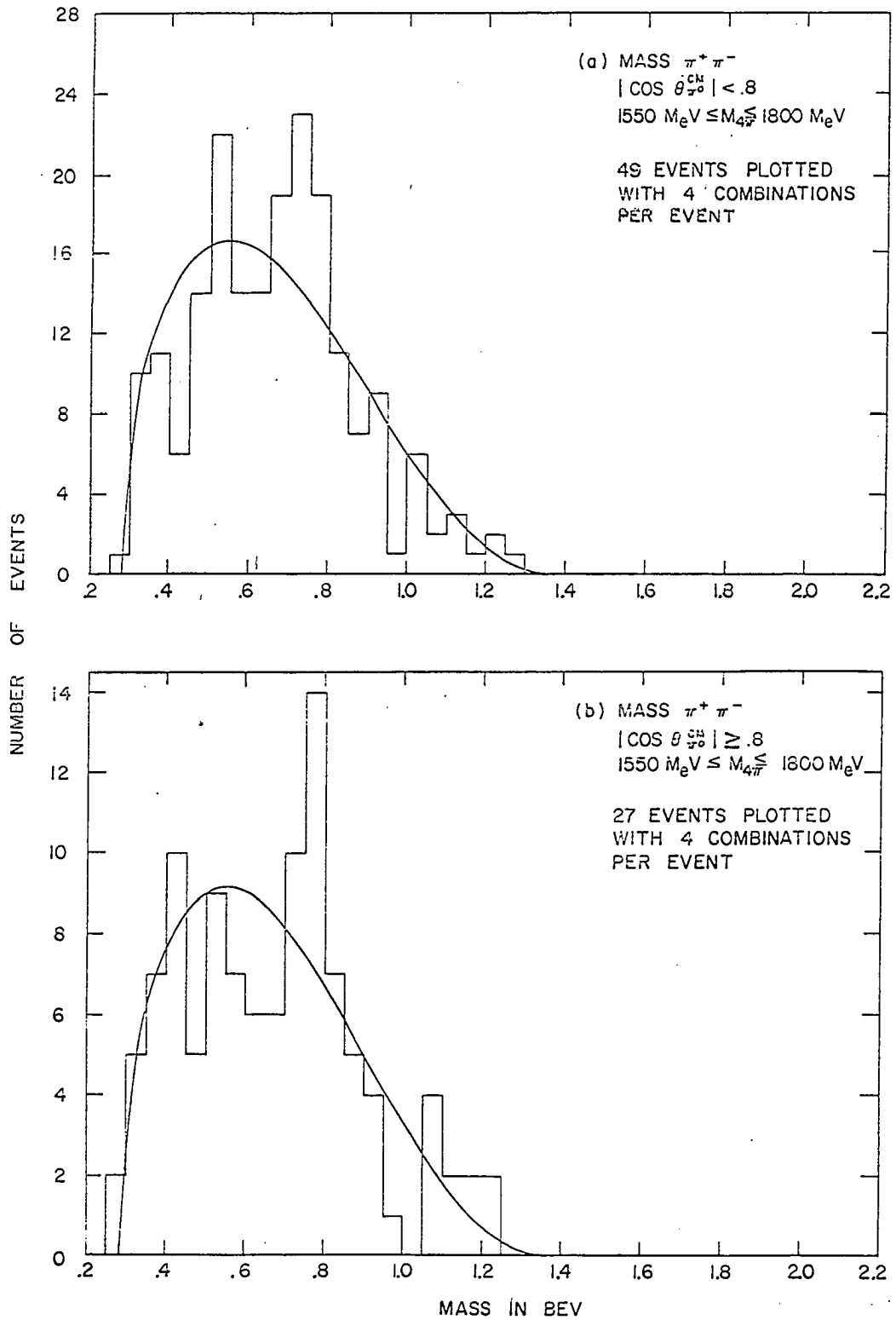


Figure 8. The smooth curves are the phase space distributions normalized to the area of each histogram.

to the background rate. To determine the excess ρ signal present due to the decay of the G meson, this background rate was subtracted from the rate determined by re-plotting the spectrum using only events with $|\cos \theta_{\pi^0}^{\text{cm}}| \geq .8$ (Figure 8b). A Dalitz plot of one $\pi^+\pi^-$ mass combination in an event versus the other $\pi^+\pi^-$ mass combination in that event for events included in Figure 8b revealed no clear evidence for ρ - ρ coincidences (Figure 9). Thus, the excess ρ signal was wholly attributed to $\rho^0\pi^+\pi^-$ decays. By estimating the background in this way for events in the classes (a), (a + b), and (a + b + c), the ratio of the number of decays via $\rho^0\pi^+\pi^-$ to all decays resulting in four pions was determined to be $.7^{+.3}_{-.5}$.

Since it is known that the G meson decays to four charged pions, one expects it to have a $\pi^+\pi^-\pi^0\pi^0$ decay mode also. To observe this decay in the four-prong data analyzed here, the reaction producing the G must be either

$$\bar{P} + P \rightarrow G + \pi^+ + \pi^-$$

or

$$\bar{P} + P \rightarrow G + \rho^0,$$

with some combination of decays of G and ρ^0 that give the $2\pi^+2\pi^-2\pi^0$ final state. These are both unconstrained reactions because of the presence of two unobserved π^0 mesons. The reaction producing G in association with ρ^0 might show the same angular correlation of the G with the antiproton direction observed when G is in association with π^0 .

If the ρ^0 decays via the $\pi^+\pi^-$ mode, then when one puts the $\pi^+\pi^+\pi^-\pi^-$ decay into either of these reactions, instead of $\pi^+\pi^-\pi^0\pi^0$, the resulting final state will have $3\pi^+$ and $3\pi^-$ mesons. An analysis of the six-prong

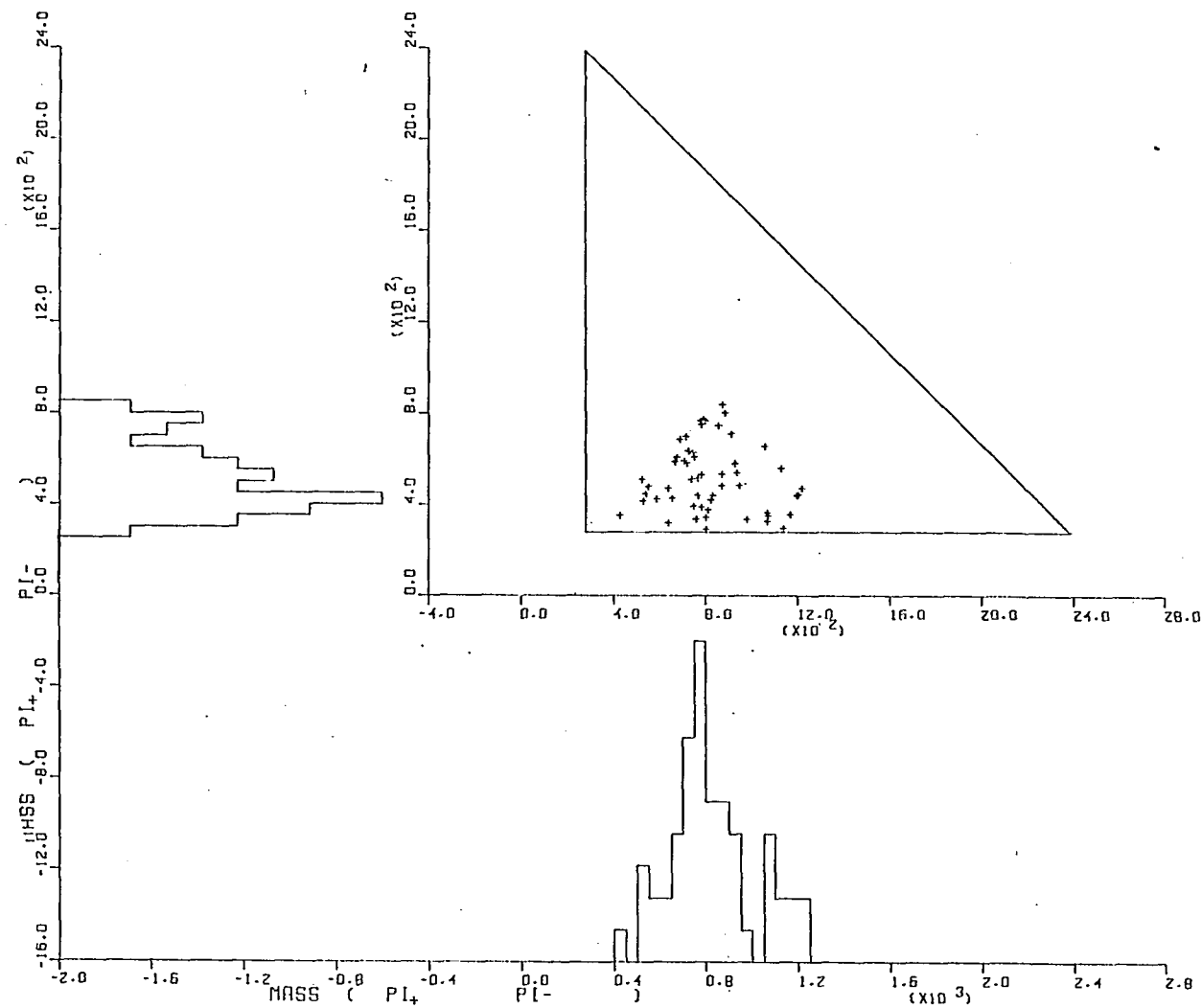


Figure 9. Folded Dalitz plot for those events where $1800 \text{ MeV} \geq M_{\pi^+\pi^-\pi^+\pi^-} \geq 1550 \text{ MeV}$, and

$|\cos \theta_{\pi^0}^{\text{cm}}| \geq .8$. The mass scales are in MeV.

events⁵, in this experiment, that have unique kinematic fits to the $3\pi^+3\pi^-$ final state gave only slight evidence for the presence of G in the $\pi^+\pi^+\pi^-\pi^-$ mass spectrum and for the presence of a ρ signal in the $\pi^+\pi^-$ spectrum that was associated with events from the 1550-1800 MeV range of the $\pi^+\pi^+\pi^-\pi^-$ mass plot. The analysis favors $G\pi^+\pi^-$ over $G\rho^0$ and thus removes hope for the angular correlation study mentioned above.

The events used in the search for the $\pi^+\pi^-\pi^0\pi^0$ decay of the G had one or more kinematic fit of some kind, but events having a fit to five pions and/or fits involving nucleons in the final state were excluded. When subjected to the hypothesis of four charged pions, it was required that each event used have a missing mass greater than 500 MeV and an effective mass for each $\pi^+\pi^-$ pair greater than 400 MeV. The first of these requirements was introduced in order to exclude real 5π events that failed to fit that hypothesis, and the second to exclude Dalitz pair events. The $\pi^+\pi^-\pi^0\pi^0$ and $\pi^+\pi^+\pi^-\pi^-$ spectra thus produced showed no evidence for the presence of the G meson, but the $\pi^0\pi^0$ and $\pi^+\pi^-$ spectra showed some ρ . However, slices of the data containing events with a $\pi^0\pi^0$ or a $\pi^+\pi^-$ mass in the ρ mass region showed no evidence for the presence of G either.

A similar analysis was performed using events that failed to fit every hypothesis tried. The results were again negative. In addition, the angular correlation study was performed with both sets of data, but it gave no positive results. When one considers the possible biases in the spectra considered and the inconclusive nature of the $3\pi^+3\pi^-$ data concerning the G meson, though, these results are not too surprising.

⁵The six-prong events are being analyzed by Daryl E. Bohning but are as yet unpublished.

IV. THE FOUR PION FINAL STATE

The effective mass spectra for $n = 2$ and 3 for the four pion final state are shown in Figure 10. Here it is seen that the three body distribution is phase space distributed, but the two body distribution shows a great deal of structure. There are only 84 events in this final state, which makes the statistical validity of such structure rather limited. However, it is interesting to note that with four $\pi^+\pi^-$ combinations for each event plotted, if a resonant state exists then at most two combinations are real. A double resonance would then give a 50% background, and this is approximately what is observed. With the appearance of strong ρ and f signals, and a two bin effect in the mass range 1600-1700 MeV that could be interpreted as the two body decay mode of the G meson, there exists the possibility that these resonances may be produced in coincidence. The Dalitz plot of this data is shown in Figure 11. The clumping of the data points in the regions of ρ - f , f - f , and ρ - G coincidences is visible in this folded plot, but the poor statistics prevents one from drawing definite conclusions. Only one fourth of the four-prong data obtained in this experiment has been analyzed so far, but the interesting nature of the four pion final state has spurred attempts to increase the statistics in this channel.

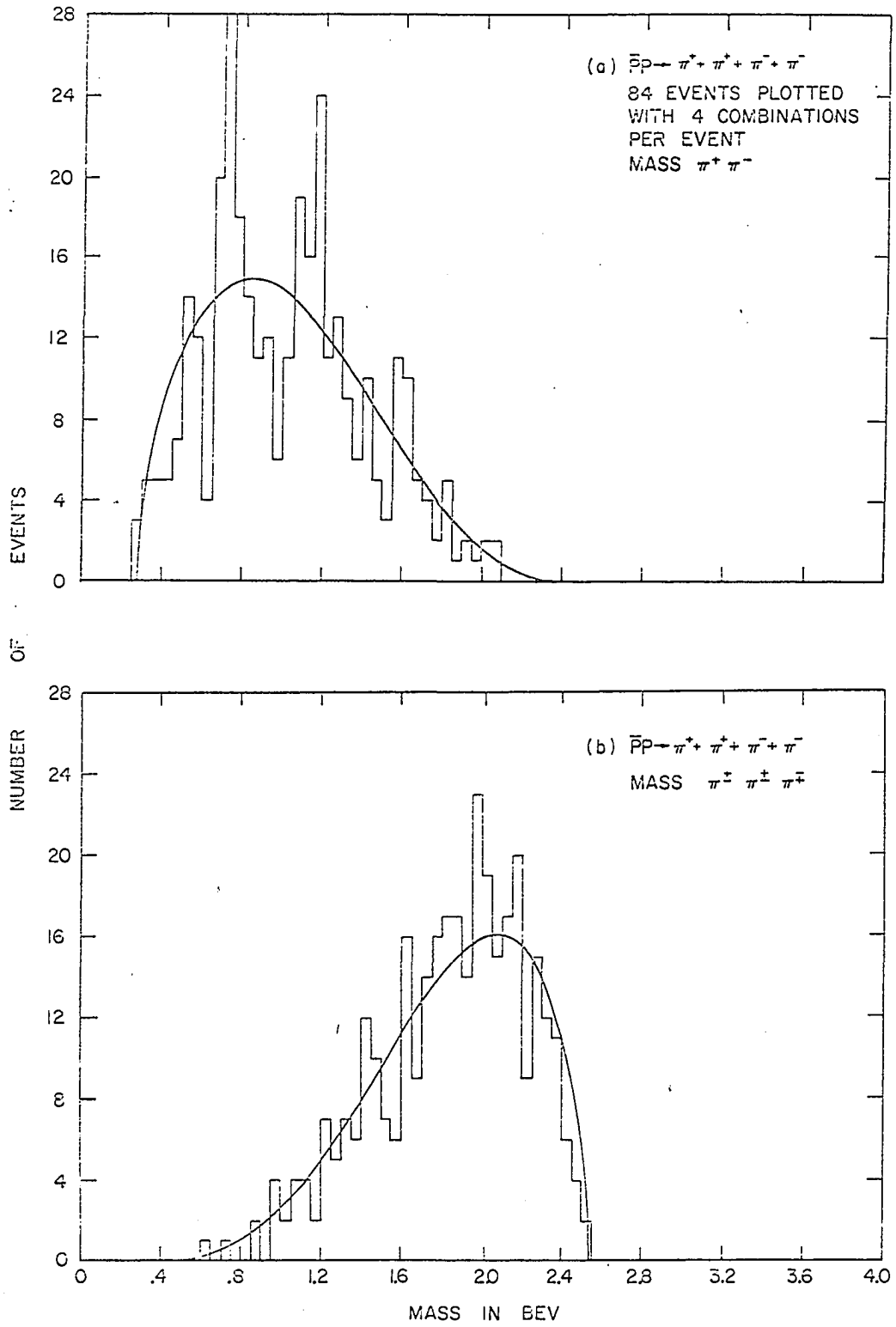


Figure 10. The smooth curves are the phase space distributions normalized to the area of each histogram.

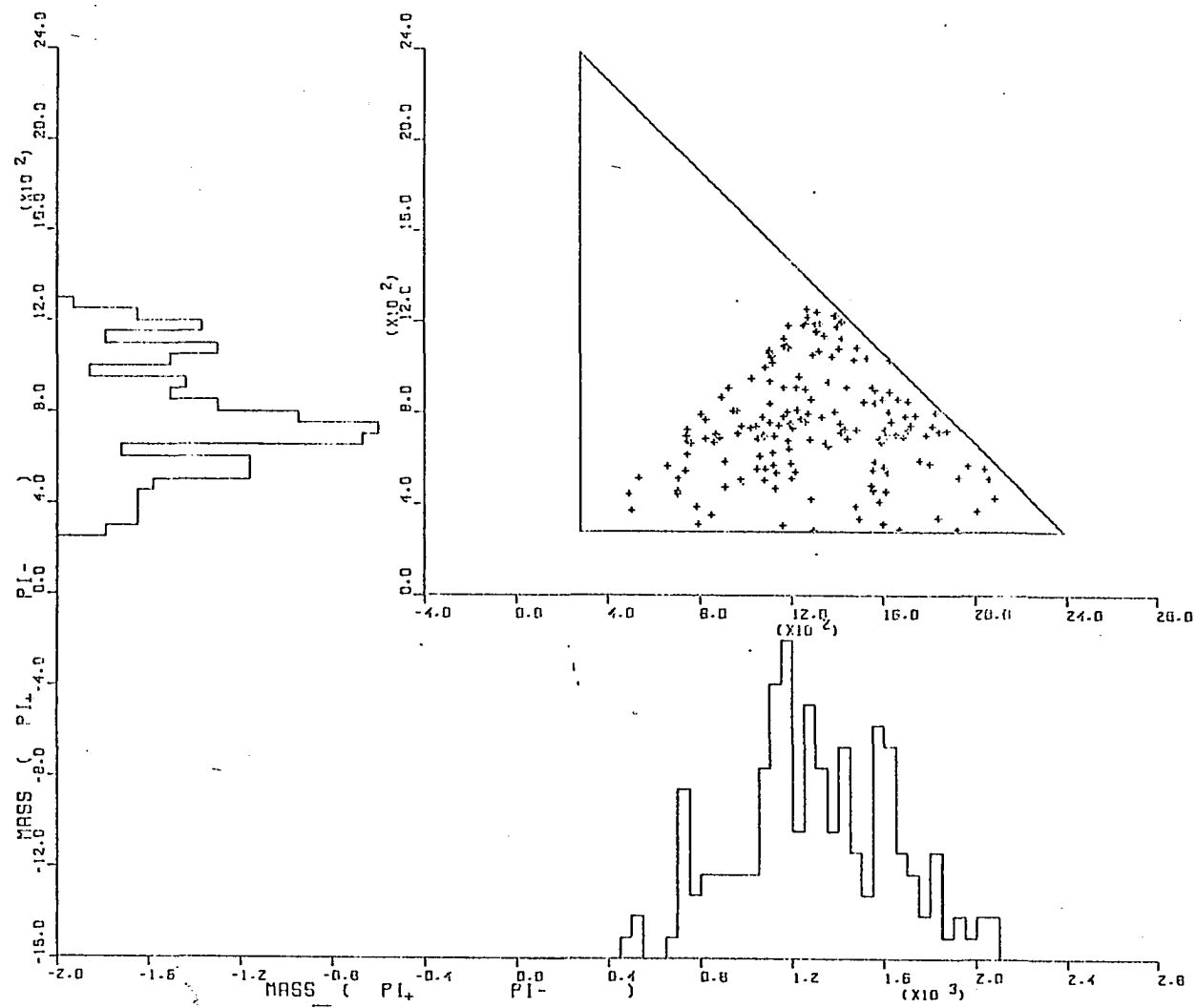


Figure 11. Folded Dalitz plot for events from the four pion channel. The mass scales are in MeV.

V. CROSS SECTIONS

Cross sections for the four and five pion final states are $(.8 \pm .1)$ mb and $(4.8 \pm .5)$ mb, respectively, while the total cross section for the $\bar{P}P$ system going to all four-prongs is (23.7 ± 0.8) mb. The four pion cross section was obtained using all 84 of the events in this channel. The number of events used to calculate the five pion cross section was the number of events in the class (a + b + c) less 18% of this number. The subtraction was made because it was found that 18% of the events in this class were $2\pi^+2\pi^-2\pi^0$ events that accidentally fit the five pion final state. The cross sections include corrections for losses due to scanning and measuring efficiencies, and due to the limits of acceptability placed on χ^2 and the missing mass.

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